Foundation of Cryptography, Lecture 6
Interactive Proofs and Zero Knowledge

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Part I

Interactive Proofs

$\mathcal{NP}$ as a Non-interactive Proofs

Definition 1 ($\mathcal{NP}$)

$\mathcal{L} \in \mathcal{NP}$ iff $\exists$ and poly-time algorithm V such that:

- $\forall x \in \mathcal{L} \cap \{0,1\}^n$ there exists $w \in \{0,1\}^*$ s.t. $\mathsf{V}(x,w) = 1$
- $\mathsf{V}(x,w) = 0$ for every $x \notin \mathcal{L}$ and $w \in \{0,1\}^*$

Only $|x|$ counts for the running time of V.

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- Efficient verifier, efficient prover (given the witness)
- Soundness holds unconditionally

Interactive proofs

Protocols between efficient verifier and unbounded provers.

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Definition 2 (Interactive proof)

A protocol (P,V) is an interactive proof for $\mathcal{L}$, if V is PPT and:

Completeness $\forall x \in \mathcal{L}$, $\Pr[\langle(\mathsf{P},\mathsf{V})(x)\rangle = 1] \geq 2/3$

Soundness $\forall x \notin \mathcal{L}$, and any algorithm P^* $\Pr[\langle(\mathsf{P}^*,\mathsf{V})(x)\rangle = 1] \leq 1/3$

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- Sometime we have efficient provers via “auxiliary input".
- Relaxation: *Computationally sound proofs* [also known as, *interactive arguments*]: soundness only guaranteed against efficient (PPT) provers.

Section 1

Interactive Proof for Graph Non-Isomorphism

Graph isomorphism

Π_m – the set of all permutations from $[m]$ to $[m]$

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Graphs $\mathsf{G}_0 = ([m], E_0)$ and $\mathsf{G}_1 = ([m], E_1)$ are isomorphic, denoted $\mathsf{G}_0 \equiv \mathsf{G}_1$, if $\exists \pi \in \Pi_m$ such that
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  Idea: Beer tasting...

Interactive proof for $\mathcal{GNI}$

Protocol 4 ((P, V))

Common input $\mathsf{G}_0 = ([m], E_0), \mathsf{G}_1 = ([m], E_1)$

1. V chooses $b \leftarrow \{0, 1\}$ and $\pi \leftarrow \Pi_m$, and sends $\pi(E_b)$ to P.[a]
2. P send b' to V (tries to set $b' = b$).
3. V accepts iff $b' = b$.

[a] $\pi(E) = \{(\pi(u), \pi(v) \colon (u, v) \in E\}$.

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Claim 5

The above protocol is IP for $\mathcal{GNI}$, with perfect completeness and soundness error $\frac{1}{2}$.

Proving Claim 5

- Graph isomorphism is an equivalence relation (separates the set of all graph pairs into separate subsets)

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$\mathrm{G}_0 \equiv \mathrm{G}_1$: $\Pr[b' = b] \leq \frac{1}{2}$.

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Hence,

$\mathrm{G}_0 \equiv \mathrm{G}_1$: $\Pr[b' = b] \leq \frac{1}{2}$.

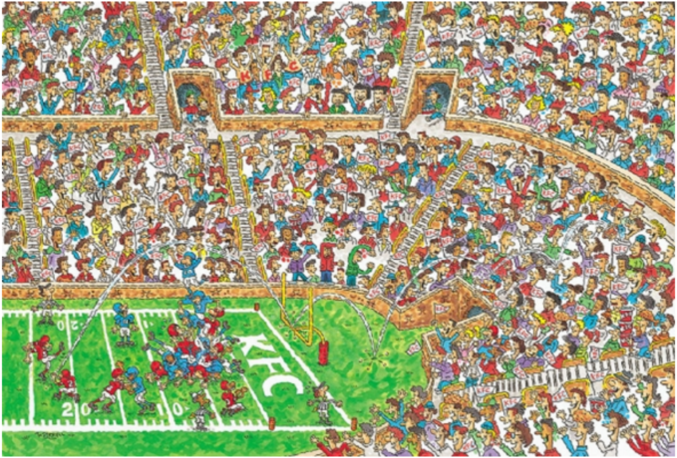
$\mathrm{G}_0 \not\equiv \mathrm{G}_1$: $\Pr[b' = b] = 1$ (i.e., P can, possibly inefficiently, extracted from $\pi(E_i)$)

□

Part II

Zero knowledge Proofs

Where is Waldo?



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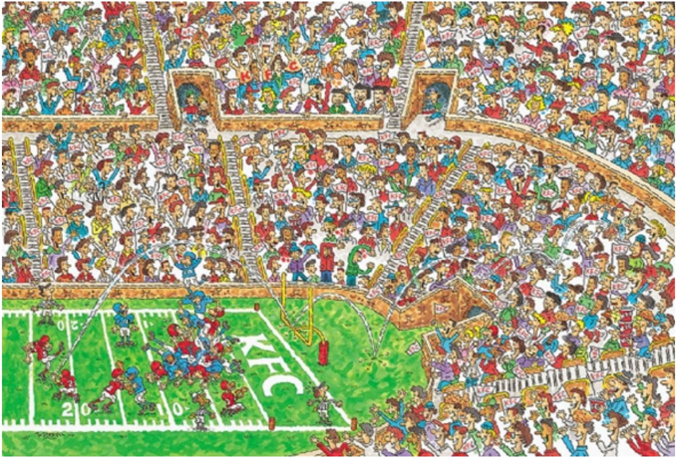

Question 6

Can you prove you know where Waldo is without revealing his location?

The concept of zero knowledge

- Proving w/o revealing any addition information.

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  Simulation paradigm.

Zero knowledge Proof

Definition 7 (zero-knowledge proofs)

An interactive proof (P, V) is computational zero-knowledge proof ($\mathcal{CZK}$) for $\mathcal{L}$, if $\forall$ PPT V^*, $\exists$ PPT S such that $\{\langle(\mathsf{P}, \mathsf{V}^*)(x)\rangle\}_{x\in\mathcal{L}} \approx_c \{\mathsf{S}(x)\}_{x\in\mathcal{L}}$.

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7. Next class — $\mathcal{ZK}$ for all $\mathcal{NP}$

Section 2

Zero-Knowledge Proof for Graph Isomorphism

$\mathcal{ZK}$ Proof for Graph Isomorphism

Idea: route finding

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Protocol 8 ((P, V))

Common input: $x = (\mathsf{G}_0 = ([m], E_0), \mathsf{G}_1 = ([m], E_1))$

P's input: a permutation π over $[m]$ such that $\pi(E_1) = E_0$.

1. P chooses $\pi' \leftarrow \Pi_m$ and sends $E = \pi'(E_0)$ to V.
2. V sends $b \leftarrow \{0, 1\}$ to P.
3. If $b = 0$, P sets $\pi'' = \pi'$, otherwise, it sends $\pi'' = \pi' \circ \pi$ to V.
4. V accepts iff $\pi''(E_b) = E$.

$\mathcal{ZK}$ Proof for Graph Isomorphism

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Claim 9

Protocol 8 is a $\mathcal{SZK}$ for $\mathcal{GI}$, with perfect completeness and soundness $\frac{1}{2}$.

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  Assuming V rejects w.p. less than $\frac{1}{2}$ and let π_0 and π_1 be the values guaranteed by the above observation (i.e., mapping E_0 and E_1 to E respectively).

  Then $\pi_0^{-1}(\pi_1(E_1)) = \pi_0 \implies (\mathsf{G}_0, \mathsf{G}_1) \in \mathcal{GI}$.

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  Then $\pi_0^{-1}(\pi_1(E_1)) = \pi_0 \implies (\mathsf{G}_0, \mathsf{G}_1) \in \mathcal{GI}$.
- $\mathcal{ZK}$: Idea – for $(\mathsf{G}_0, \mathsf{G}_1) \in \mathcal{GI}$, it is easy to generate a random transcript for Steps 1-2, and to be able to open it with prob $\frac{1}{2}$.

The simulator

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Algorithm 10 (S)

Input: $x = (\mathsf{G}_0 = ([m], E_0), \mathsf{G}_1 = ([m], E_1))$

Do $|x|$ times:

1. Choose $b' \leftarrow \{0,1\}$ and $\pi \leftarrow \Pi_m$, and “send" $\pi(E_{b'})$ to $\mathsf{V}^*(x)$.
2. Let b be V^*'s answer. If $b = b'$, send π to V^*, output V^*'s output and halt. Otherwise, rewind V^* to its initial step, and go to step 1.

Abort.

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Claim 11

$\{\langle (P, V^*)(x)\rangle\}_{x \in \mathcal{GI}} \approx \{S(x)\}_{x \in \mathcal{GI}}$

where $\langle (P, V^*)(x)\rangle$ describes the parties' join output in a random execution of (P, V^*) on input x.

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Claim 11 implies that Protocol 8 is zero knowledge. (?)

Proving Claim 11

Consider the following inefficient simulator:

Algorithm 12 (S')

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1. Choose $\pi \leftarrow \Pi_m$ and send $E = \pi(E_0)$ to $V^*(x)$.
2. Let b be V^*'s answer.

   W.p. $\frac{1}{2}$,

   1. Find π' such that $E = \pi'(E_b)$, and send it to V^*.
   2. Output V^*'s output and halt.

   Otherwise, rewind V^* to its initial step, and go to step 1.

Abort.

Proving Claim 11

Consider the following inefficient simulator:

Algorithm 12 (S′)

Input: $x = (\mathsf{G}_0 = ([m], E_0), \mathsf{G}_1 = ([m], E_1))$.

Do $|x|$ times:

1. Choose $\pi \leftarrow \Pi_m$ and send $E = \pi(E_0)$ to $\mathsf{V}^*(x)$.
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Proof: ?

Proving Claim 11 cont.

Consider a second inefficient simulator:

Algorithm 14 (S'')

Input: $x = (G_0 = ([m], E_0), G_1 = ([m], E_1))$

1. Choose $\pi \leftarrow \Pi_m$ and send $E = \pi(E_0)$ to $V^*(x)$.
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$\forall x \in \mathcal{GI}$ it holds that

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Proof: ? (1) is clear.

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Fix (E, π') and let $\alpha = \Pr_{S''(x)}[(E, \pi')]$.

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Hence, $SD(S''(x), S'(x)) \leq 2^{-|x|} \Box$

Remarks

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6. “Black box" simulation

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Protocol 16 ((P, V))

Common input: $x \in \{0,1\}^*$

P's input: $w \in R_{\mathcal{L}}(x)$

1. V chooses $(d, e) \leftarrow \mathsf{G}(1^{|x|})$ and sends e to P
2. P sends $c = \mathsf{E}_e(w)$ to V
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- It has "transcript simulator" (at least for honest verifiers): exits PPT S such that $\{\langle(\mathsf{P}(w \in R_{\mathcal{L}}(x)), \mathsf{V})(x)\rangle\}_{x\in\mathcal{L}} \approx_c \{\mathsf{S}(x)\}_{x\in\mathcal{L}}$,

  where *trans* stands for the transcript of the protocol (i.e., the messages exchange through the execution).

Section 3

Black-box Zero Knowledge

Black-box simulators

Definition 17 (Black-box simulator)

(P,V) is $\mathcal{CZK}$ with black-box simulation for $\mathcal{L}$, if $\exists$ oracle-aided PPT S s.t.

$$\{(\mathsf{P}(w_x),\mathsf{V}^*(z_x))(x)\}_{x\in\mathcal{L}} \approx_c \{\mathsf{S}^{\mathsf{V}^*(x,z_x)}(x)\}_{x\in\mathcal{L}}$$

for any deterministic polynomial-time[a] V^* and $\{(w_x,z_x)\in R_{\mathcal{L}}(x)\times\{0,1\}^*\}_{x\in\mathcal{L}}$.

Prefect and statistical variants are defined analogously.

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1. What about randomized verifier?
2. “Most simulators" are black box
3. Strictly weaker then general simulation!

Section 4

Zero Knowledge for all NP

$\mathcal{CZK}$ for 3COL

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We use commitment schemes.

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Protocol 19 ((P, V))

Common input: Graph $\mathsf{G} = (M, E)$ with $n = |\mathsf{G}|$

P's input: a (valid) coloring ϕ of G

1. P chooses $\pi \leftarrow \Pi_3$ and sets $\psi = \pi \circ \phi$
2. $\forall v \in M$: P commits to $\psi(v)$ using Com (with security parameter 1^n).
   Let c_v and d_v be the resulting commitment and decommitment.
3. V sends $e = (u, v) \leftarrow E$ to P
4. P sends $(d_u, \psi(u)), (d_v, \psi(v))$ to V
5. V verifies that
   1. Both decommitments are valid,
   2. $\psi(u), \psi(v) \in [3]$, and
   3. $\psi(u) \neq \psi(v)$.

Claim 20

The above protocol is a $\mathcal{CZK}$ for 3COL, with perfect completeness and soundness $1/|E|$.

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- Soundness: Let $\{c_v\}_{v \in M}$ be the commitments resulting from an interaction of V with an arbitrary P*.

  Define $\phi\colon M \mapsto [3]$ as follows:

  $\forall v \in M$: let $\phi(v)$ be the (single) value that it is possible to decommit c_v into (if not in [3], set $\phi(v) = 1$).

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  If $G \notin 3COL$, then $\exists (u, v) \in E$ s.t. $\psi(u) = \psi(v)$.

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  Hence V rejects such x w.p. a least $1/|E|$

Proving $\mathcal{ZK}$

Fix a deterministic, non-aborting V^* that gets no auxiliary input.

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Algorithm 21 (S)

Input: A graph $\mathsf{G} = (M, E)$ with $n = |\mathsf{G}|$

Do $n \cdot |E|$ times:

1. Choose $e' = (u, v) \leftarrow E$.
   1. Set $\psi(u) \leftarrow [3]$,
   2. Set $\psi(v) \leftarrow [3] \setminus \{\psi(u)\}$, and
   3. Set $\psi(w) = 1$ for $w \in M \setminus \{u, v\}$.
2. $\forall v \in M$: commit to $\psi(v)$ to V^* (resulting in c_v and d_v)
3. Let e be the edge sent by V^*.

   If $e = e'$, send $(d_u, \psi(u)), (d_v, \psi(v))$ to V^*, output V^*'s output and halt.

   Otherwise, rewind V^* to its initial step, and go to step 1.

Abort.

Proving $\mathcal{ZK}$ cont.

Claim 22

$\{(\mathsf{P}(w_x), \mathsf{V}^*)(x)\}_{x \in 3\mathrm{COL}} \approx_c \{\mathsf{S}^{\mathsf{V}^*(x)}(x)\}_{x \in 3\mathrm{COL}}$, for any $\{w_x \in R_{3\mathrm{COL}}(x)\}_{x \in 3\mathrm{COL}}$.

Consider the following (inefficient simulator)

Algorithm 23 (S')

Input: $\mathsf{G} = (V, E)$ with $n = |\mathsf{G}|$

Find (using brute force) a valid coloring ϕ of G

Do for $n \cdot |E|$ times:

1. Act like the honest prover does given private input ϕ.
2. Let e be the edge sent by V^*. W.p. $1/|E|$,
   1. Send $(\psi(u), d_u), (\psi(v), d_v)$ to V^*,
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Claim 24

$\{\mathsf{S}^{\mathsf{V}^*(x)}(x)\}_{x \in 3\mathrm{COL}} \approx_c \{\mathsf{S}'^{\mathsf{V}^*(x)}(x)\}_{x \in 3\mathrm{COL}}$

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   Otherwise, rewind V^* to its initial step, and go to step 1.

Abort.

Claim 24

$\{S^{V^*(x)}(x)\}_{x \in 3COL} \approx_c \{S'^{V^*(x)}(x)\}_{x \in 3COL}$

Proof: ?

Proving Claim 24

Assume $\exists$ PPT D, $p \in$ poly and an infinite set $\mathcal{I} \subseteq$ 3COL s.t.

$$\left|\Pr[\mathsf{D}(|x|, \mathsf{S}^{\mathsf{V}^*(x)}(x)) = 1] - \Pr[\mathsf{D}(|x|, \mathsf{S'}^{\mathsf{V}^*(x)}(x)) = 1]\right| \geq 1/p(|x|)$$

for all $x \in \mathcal{I}$.

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for all $x \in \mathcal{I}$.

Hence, $\exists$ PPT R^* and $b \in [3] \setminus 1$ such that

$$\{\mathsf{View}_{\mathsf{R}^*}(\mathsf{Snd}(1), \mathsf{R}^*(x))(1^{|x|})\}_{x\in\mathcal{I}} \not\approx_c \{\mathsf{View}_{\mathsf{R}^*}(\mathsf{Snd}(b), \mathsf{R}^*(x))(1^{|x|})\}_{x\in\mathcal{I}}$$

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We critically used the non-uniform security of Com.

S' is a good simulator

Claim 25

$\{(\mathsf{P}(w_x), \mathsf{V}^*)(x)\}_{x \in 3\mathrm{COL}} \approx_c \{\mathsf{S}'^{\mathsf{V}^*(x)}(x)\}_{x \in 3\mathrm{COL}}$, for any $\{w_x \in R_{\mathcal{GI}}(x)\}_{x \in 3\mathrm{COL}}$.

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Proof: ?

Remarks

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Remarks

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Remarks

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Extending to all $\mathcal{NP}$

For $\mathcal{L} \in \mathcal{NP}$ let Map_X and Map_W be two poly-time functions s.t.

- $x \in \mathcal{L} \iff \mathsf{Map}_X(x) \in \mathsf{3COL}$,

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- $(x, w) \in R_{\mathcal{L}} \iff \mathsf{Map}_W(x, w) \in R_{\mathsf{3COL}}(\mathsf{Map}_X(x))$

Extending to all $\mathcal{NP}$

For $\mathcal{L} \in \mathcal{NP}$ let Map_X and Map_W be two poly-time functions s.t.

- $x \in \mathcal{L} \iff \mathsf{Map}_X(x) \in \mathsf{3COL}$,
- Map_X is efficiently invertible.
- $(x, w) \in R_{\mathcal{L}} \iff \mathsf{Map}_W(x, w) \in R_{\mathsf{3COL}}(\mathsf{Map}_X(x))$

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Protocol 26 ($(\mathsf{P}_{\mathcal{L}}, \mathsf{V}_{\mathcal{L}})$)

Common input: $x \in \{0, 1\}^*$.

$\mathsf{P}_{\mathcal{L}}$'s input: $w \in R_{\mathcal{L}}(x)$.

1. The two parties interact in $\langle(\mathsf{P}(\mathsf{Map}_W(x, w)), \mathsf{V})(\mathsf{Map}_X(x))\rangle$, where $\mathsf{P}_{\mathcal{L}}$ and $\mathsf{V}_{\mathcal{L}}$ taking the role of P and V respectively.
2. $\mathsf{V}_{\mathcal{L}}$ accepts iff V accepts in the above execution.

Extending to all $\mathcal{L} \in \mathcal{NP}$ cont.

Claim 27

$(\mathsf{P}_{\mathcal{L}}, \mathsf{V}_{\mathcal{L}})$ is a $\mathcal{CZK}$ for $\mathcal{L}$ with the same completeness and soundness as (P, V) as for 3COL.

Extending to all $\mathcal{L} \in \mathcal{NP}$ cont.

Claim 27

$(\mathsf{P}_{\mathcal{L}}, \mathsf{V}_{\mathcal{L}})$ is a $\mathcal{CZK}$ for $\mathcal{L}$ with the same completeness and soundness as (P, V) as for 3COL.

- Completeness and soundness: Clear.

Extending to all $\mathcal{L} \in \mathcal{NP}$ cont.

Claim 27

$(\mathsf{P}_{\mathcal{L}}, \mathsf{V}_{\mathcal{L}})$ is a $\mathcal{CZK}$ for $\mathcal{L}$ with the same completeness and soundness as (P, V) as for 3COL.

- Completeness and soundness: Clear.
- Zero knowledge: Let S (an efficient) $\mathcal{ZK}$ simulator for (P, V) (for 3COL). Define $\mathsf{S}_{\mathcal{L}}(x)$ to output $\mathsf{S}(\mathsf{Map}_X(x))$, while replacing the string $\mathsf{Map}_X(x)$ in the output of S with x.

Extending to all $\mathcal{L} \in \mathcal{NP}$ cont.

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Claim 28

$\{(\mathsf{P}_\mathcal{L}(w_x), \mathsf{V}^*_\mathcal{L})(x)\}_{x \in \mathcal{L}} \approx_c \{\mathsf{S}_\mathcal{L}^{\mathsf{V}^*_\mathcal{L}(x)}(x)\}_{x \in \mathcal{L}}$ for any PPT $\mathsf{V}^*_\mathcal{L}$.

Extending to all $\mathcal{L} \in \mathcal{NP}$ cont.

Claim 27

$(\mathsf{P}_{\mathcal{L}}, \mathsf{V}_{\mathcal{L}})$ is a $\mathcal{CZK}$ for $\mathcal{L}$ with the same completeness and soundness as (P, V) as for 3COL.

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$\{(\mathsf{P}_{\mathcal{L}}(w_x), \mathsf{V}^*_{\mathcal{L}})(x)\}_{x \in \mathcal{L}} \approx_c \{\mathsf{S}_{\mathcal{L}}^{\mathsf{V}^*_{\mathcal{L}}(x)}(x)\}_{x \in \mathcal{L}}$ for any PPT $\mathsf{V}^*_{\mathcal{L}}$.

Extending to all $\mathcal{L} \in \mathcal{NP}$ cont.

Claim 27

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Proof:

Extending to all $\mathcal{L} \in \mathcal{NP}$ cont.

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Proof: Assume $\{(\mathsf{P}_{\mathcal{L}}(w_x), \mathsf{V}^*_{\mathcal{L}})(x)\}_{x\in\mathcal{L}} \not\approx_c \{\mathsf{S}_{\mathcal{L}}^{\mathsf{V}^*_{\mathcal{L}}(x)}(x)\}_{x\in\mathcal{L}}$ for some $\mathsf{V}^*_{\mathcal{L}}$.

Extending to all $\mathcal{L} \in \mathcal{NP}$ cont.

Claim 27

$(\mathsf{P}_\mathcal{L}, \mathsf{V}_\mathcal{L})$ is a $\mathcal{CZK}$ for $\mathcal{L}$ with the same completeness and soundness as (P, V) as for 3COL.

- Completeness and soundness: Clear.
- Zero knowledge: Let S (an efficient) $\mathcal{ZK}$ simulator for (P, V) (for 3COL).

  Define $\mathsf{S}_\mathcal{L}(x)$ to output $\mathsf{S}(\mathsf{Map}_X(x))$, while replacing the string $\mathsf{Map}_X(x)$ in the output of S with x.

Claim 28

$\{(\mathsf{P}_\mathcal{L}(w_x), \mathsf{V}^*_\mathcal{L})(x)\}_{x\in\mathcal{L}} \approx_c \{\mathsf{S}_\mathcal{L}^{\mathsf{V}^*_\mathcal{L}(x)}(x)\}_{x\in\mathcal{L}}$ for any PPT $\mathsf{V}^*_\mathcal{L}$.

Proof: Assume $\{(\mathsf{P}_\mathcal{L}(w_x), \mathsf{V}^*_\mathcal{L})(x)\}_{x\in\mathcal{L}} \not\approx_c \{\mathsf{S}_\mathcal{L}^{\mathsf{V}^*_\mathcal{L}(x)}(x)\}_{x\in\mathcal{L}}$ for some $\mathsf{V}^*_\mathcal{L}$.

It follows that $\{(\mathsf{P}(\mathsf{Map}_W(x, w_x)), \mathsf{V}^*)(x)\}_{x\in 3\mathrm{COL}} \not\approx_c \{\mathsf{S}^{\mathsf{V}^*(x)}(x)\}_{x\in 3\mathrm{COL}}$.

$\mathsf{V}^*(x)$: act like $\mathsf{V}^*_\mathcal{L}(x')$ for $x' = \mathsf{Map}_X^{-1}(x)$.